

Overview of the national efforts for improving highway bridge maintenance technology in Japan

**Atsushi Yoshioka, Shoichi Nakatani, Jun Murakoshi, Yoshitomi Kimura,
Jun-ichi Hoshikuma, and Masahiro Shirato**

*Bridges and Structures Research Group,
Center for Advanced Engineering Structural Assessment and Research (CAESAR)
Public Works Research Institute (PWRI)
1-6 Minamihara, Tsukuba, 305-8516 Ibaraki, Japan*

Abstract

With recent rapid increase in demand for structural condition assessment and rehabilitation of existing highway bridges the Center for Advanced Engineering Structural Assessment and Research, CAESAR, was established in April 2008, as the national agency of the research and development of design, construction, and maintenance for highway bridges. This paper presents national efforts for improving highway bridge maintenance technology, seeing some of the highlight missions and research projects of the new organization, CAESAR.

1. INTRODUCTION

The maintenance of older bridges is a national growing concern. The needs for structural repair and rehabilitation tend to increase as the bridge becomes older. The majority of highway bridges in Japan were constructed during the 1950s–1970s, which coincides with Japan's high-growth period, and the number of bridges over 50 years old will increase drastically in the coming years. Highway bridges in Japan are exposed to severe automobile traffic and natural environment; it is highly probable that the deterioration and damage will increase rapidly. Consequently, under tight financial circumstances, technologies related to inspection, prognosis, diagnosis, repair, and reinforcement should be established urgently.

On top of that, as well known, disaster prevention and mitigation technologies are crucial in Japan. Even in the last two decades, infrastructure was heavily damaged by the Hyogo-ken Nanbu (Kobe) Earthquake in 1995, the Niigata Chuetsu Earthquake in 2004, the Noto Peninsula Earthquake and Niigata Chuetsu-Oki Earthquake in 2007. Maintenance in Japan is not only for preventing the deterioration but only for upgrading the seismic performance and the prioritization is getting more and more important.

Let's face some statistics [1]. Figure 1 portrays a comparison of the numbers of highway bridges by year built in Japan and the U.S. As a whole, bridges in Japan are about 30 years younger than those in the U.S. Figure 2 also shows that the number of highway bridges older than 50 years is increasing, where bridges no shorter than 15 m are counted. Bridges go through a natural deterioration and aging process. The statistical data indicate that, by 2026, 47% of Japan's highway bridges will be older than 50 years, where the total number of which was approximately 140,000 as of 2006. The construction of the national highway network system is still under the way, but we are entering the maintenance era. As shown in Figure 3, many instances of damage such as the fatigue cracks in steel floor slabs and girders and the salt corrosion and alkali-silica reaction of concrete members have already appeared as the national major defects, which strongly influence bridge load-bearing characteristics.

Accordingly, the government bridge inspection program was updated in 2003 and an every-five-year hands-on inspection is now mandated for bridges on the national essential highway routes administrated by the government. Nevertheless, as shown in Figure 4, in 2007, a tension diagonal bracing of steel truss that went through the section embedded inside the deck concrete fractured in Kiso River Oh-hashii Bridge on National Route 23 because of corrosion that invisibly progressed inside the concrete. The bridge was inspected at the every-five-year hands-on inspection

and the fact of the fracture clearly indicates that severe corrosion in truss bars covered in concrete is not found out in the hands-on inspection. Then a nation-wide urgent inspection program was issued for steel truss bridges with similar details, requiring exposing all the concrete-covered portion of truss bars. In the urgent inspection program, a similar failure occurred in Honjyo Oh-hashii Bridge on National Route 7 during the work for exposing a truss bar from concrete and serious corrosions were found out in several bridges.

Regarding overseas trouble, the I-35W Bridge (Minneapolis, Minnesota, U.S.) collapsed in August 2007 despite the fact that detailed inspections and status assessments had been carried out annually [2, 3]. The collapse of the de la Concorde overpass in Quebec, Canada, killed five people, even though the bridge was inspected routinely and at that day [4]. These facts also clearly indicate the limit of hands-on inspection.

Based on these backgrounds, the Expert Meeting on Preventive Maintenance of Highway Bridges was convened by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) in FY2007 and they set out the recommendations such as:

- Establishment of a national center of excellence in the R&D of highway bridge maintenance and regional core organizations to push the preventive maintenance of highway bridges
- Legislation of bridge inspection and qualification of engineers

Then, the PWRI and MLIT established CAESAR (Center for Advanced Engineering Structural Assessment and Research) in the Public Works Research Institute (PWRI) as the nation's core research agency in April, 2008. This is a comprehensive research organization examining issues related to highway bridges including bridge design and construction technology, maintenance and management technology, long-life technology, and disaster mitigation to stay ahead of the problems caused by such decay. This paper tackles to summarize the national efforts for improving highway bridge maintenance technology in Japan via the overview of some of the CAESAR's highlight research projects.

2. NATIONAL EFFORTS

Highway administrators have tended to repair bridges that have significantly deteriorated over time. Needless to say, codes of practice for the inspection, evaluation and rehabilitation methods for major types of deterioration such as the corrosion and fatigue of steel structures and the chloride-induced deterioration and alkali silica reaction (ASR) of concrete structures have been developed and issued by the government and government agencies such as MLIT, NILIM, and CAESAR, in which NILIM is the National Institute for Land and Infrastructure Management and an organization of MLIT. However, as stated above, a number of bridges were constructed during the legendary rapid economic growth era and they are getting older. Highway administrators simply cannot keep up with the rehabilitation and replacement of aging bridges under budget restrictions. Accordingly, the extension of the life expectancy and the equalization of the year-by-year numbers of replacements should be achieved.

Accordingly, a preventive maintenance strategy is considered to be a key to thrive in the rapid aging of highway bridges in Japan. Namely, the periodical inspection and relevant maintenance at the right time with the right method should be conducted before the bridge will reach a fatal defect. The national government already has started applying a preventive maintenance strategy to their bridges. The continual and mandatory every-five-year bridge inspection was officially issued and the long-term preventive maintenance program was established by the government regional bureaus. Figure 5 illustrates an organizational chart for the maintenance of highway bridges operated by the national government. The government headquarters, MLIT's regional bureau, and two national institute and agency are cooperated. MLIT regional bureaus are the administrators of national essential highway routes and they conduct construction and maintenance of bridges on the routes. They storage bridge inspection data and track down the condition of their bridges. A policy making that we call the macroscopic management is conducted by the headquarters and NILIM of MLIT. They measure the bridge performance at the national level and make national bridge management initiatives and funding. They notify national directions for the maintenance of bridges. CAESAR conducts R&D at a microscopic level of management and supports highway administrators -- that is, a customized diagnosis, prognosis, and rehabilitation aimed at preventing individual older bridges from critical failure. This policy is established because individual bridges were designed and constructed under their specific individual conditions and each bridge aged in the way it went. In addition, traffic and environmental conditions are different for each bridge, and their maintenance histories are different as well. CAESAR's research results and rich experience are incorporated into the inspection, repair, and rehabilitation directions and even to the future design standards.

As indicated by Figure 6, local highway administrators, especially community governments, did not have a bridge inspection program or a strategic maintenance program. According to a report

from MLIT [1], 684 bridges administrated by local governments are operated with load limits or closed as of September, 2007, and almost a half of them are attributed to damage or deterioration of structural components of super- or sub-structures, and the others are attributed to functionally obsolete. Accordingly, the MLIT initiated a subsidy program for local governments to inspect their bridges and establish their long-term bridge maintenance program until FY2012 for prefectures and FY2014 for community governments. Only the bridges involved in their long-term bridge maintenance program will be eligible for the government funding to fix or replace after FY2010. With this national effort from the new construction era to the preventive maintenance era, CAESAR is delegated to strongly support local highway administrators when they have serious structural safety concern for their bridge.

3. ISSUES TO BE SOLVED

Inspection

So far, the national government subsidy program for local governments to establish their long term maintenance program promotes them to inspect their road bridges, but it is not sure that they will conduct the periodical thorough inspection for all their bridges of all structural components. We need a sustainable bridge inspection program. A thorough inspection is needed to predict the deterioration rate and life cycle cost for individual bridges listed in the long-term maintenance program, while bridges not listed in the long-term maintenance program should be at least checked if there is no expectation for the fatal failure. The frequency and items of inspection should be determined based on scientific data for both needs, respectively. However, we have just obtained a database of national bridge inspection results to analyze the change in deterioration and its transition rate and the factors that really affects the deterioration rate. We do not have a long-term observational data of bridges outside laboratories, either, enough to furnish an eligible model that is associated with the environmental and traffic conditions in Japan.

In terms of the microscopic management, first, as has been seen in Figure 4, while bridges are large, serious damage that is likely to lead to a fatal failure develops at tiny and/or hidden parts. Similar structural parts in the same bridge or similar type bridges do not always have a similar deteriorated state. Namely, structural conditions are different bridge by bridge even though they have a similar construction type and environmental and traffic conditions. Accordingly, current technology in inspection is not good enough to find out such fatal damage hiding behind a tiny portion of a total bridge system. Non-destructive testing (NDT) tools are widely used in other industrial fields but the objects and required accuracy are different for bridge inspection. So far there are no powerful and eligible non-destructive testing tools in bridge inspection. Underground and underwater inspection is also a matter.

Condition assessment and repair/rehabilitation

Figure 7 shows Choushi Oh-hashhi Bridge that was opened in 1962. The annual average daytime traffic is 20,000 with 10% of heavy vehicles. The bridge spanned over a large river mouth on the shore line. For more than 40 years, the bridge had been attacked by salt from the sea and heavily corroded. Fatigue damage was also concerned because of frequent truck loads. Comprehensive corrosion remedy and proofing measures were implemented several times, spending more than four billion yen in total expenditure. Nevertheless it was decommissioned this year at 47 years old, because the deterioration such as corrosion and fatigue was unlikely to stop and it is considered to be impossible to assess how short the remaining strength was and how soon it would failure. The short of seismic performance was also a reason to be replaced. These facts clearly indicate that the repair and rehabilitation at the right time with the right choice are very difficult.

One other thing that the fact about Choushi Oh-hashhi Bridge suggests is that it is still a matter to evaluate the necessity of replacement. Several parts of the bridge seemed severely damaged, while there was no effective measure to assess the remaining strength of the total bridge system with the uncertain loss of sectional areas and fatigue cracks covered under the multi paint layers.

The preventive maintenance should be conducted in the early stages of deterioration before the bridge will reach the rapid deterioration state. However, many types of deterioration exist and they have different mechanisms and progressing rates depending on positions in a bridge and depending on bridge by bridge with different initial construction qualities and surrounded environments, and, again, we do not have a long-term observational data outside laboratories enough to furnish an eligible model. As for concrete structures, similar problems are acknowledged. For example, there is no tool to measure the corrosion state of PC cables inside the concrete. Required accuracy to inspect such deterioration sufficient to assess the remaining strength or life expectancy has not been clarified, either.

On top of that, the rehabilitation and seismic reinforcement of older bridges involve a much more multifaceted and complicated series of issues than those encountered during conventional design/construction efforts. For older bridges, a comprehensive structural assessment of the entire structure is often required. For example, when designing a seismic reinforcement of an existing steel bridge, the structure's overall state of deterioration and the possible negative side effects of the planned reinforcement method on the fatigue vulnerability must be taken into account.

Macroscopic management

With serious budget restrictions, it is necessary to develop the prioritization and strategic maintenance programs, legislations, and regulations to hold together nation's aging bridges. Seismic retrofit is another public request and should be conducted as well as the preventive maintenance. All things should be set in a particular strategy. The performance measures for the effectiveness and sustainability of such programs, legislations, and regulations are also needed.

4. DRIVING POINTS TO SUCCESSFUL R&D

As stated above, fatigue fracture in some types of steel decks has been one of the major distresses in Japan. An example is shown in Figure 8. Some traffic accidents occurred because of it. Now a feasible NDT tool and a useful reinforcement method are available and used in the field, which have been developed by CAESAR.

Figure 9 shows a summary of the ultrasonic test tool to detect fatigue cracks in orthotropic steel decks. Since the crack's initiation and propagation are invisible, an NDT tool has been needed. The tool uses an angle beam technique with SV waves. The angle beam technique with SV waves has been already used in inspection in other industries, but the way to shot SV waves and analyze the reflections had to be improved to detect cracks with a prescribed resolution level that enables to find out the crack hidden in the welding part between U-ribs and deck floor and with a scale that cannot be neglected to prevent from penetrating entirely over the deck plate thickness. To also come in handy in the field, the sensor and rail system was made so that the sensor can move on the rail back and forth along U-ribs. The key points for this successful case are: first the mechanism of fatigue crack and the positions and direction of such cracks were understood via many laboratory tests and field observations; and second we collaborated with industrial partners in other engineering fields and showed clear specifications what we needed in terms of the required resolution level and accuracy.

We also have developed a method to improve the fatigue durability of steel deck using steel fiber reinforced concrete (SFRC) pavement. A summary is shown in Figure 10. The system consists of SFRC pavement, adhesion glue, studs, and CFRP grid. Because SFRC increases the rigidity and decreases the deformation of steel deck, the stress concentration due to localized bending in the U-rib welding is reduced even when double-tire moves on a deck plate with asphalt pavement. Adhesive is used to make pavement and deck plate composite. Studs are aligned along the edge of SFRC. CFRP grid is placed at the location of main girder web as reinforcement. The driving points to this successful case are: first, in earlier years, we had developed a fatigue resistance test protocol using a Wheel Running Testing Machine in the laboratory and understood that the reduction of localized bending deformation along the U-rib welding portion is necessary; second SFRC pavement had already existed as one of the pavement techniques; and third we can identify a relevant adhesive material that meets the toughness against actual traffic and environmental conditions out of many types of adhesive, based on the Wheel Running Test Protocol and collaborating with industrial partners.

Namely, it is equally important for bridge engineering to search a method in and out of the bridge engineering field and collaborate with industry as well as to take responsibility to understand the mechanism of distress and show the clear goals and required performance for NDT tools and repair method/material.

5. RESEARCH AND DEVELOPMENT BASED ON SCIENTIFIC TRIALS AND AN AUTOPSY APPROACH

CAESAR keeps many basic research projects going in the laboratory to understand the mechanism of deterioration and repair. However, CAESAR will keep going not only as the way we did in the laboratory but also promote a scientific trial approach in the field much more. Structural conditions, construction status (initial construction quality, etc.), and environmental and traffic conditions are different bridge by bridge. Therefore, CAESAR assigns greater importance to a scientific trial approach to resolve technical issues for maintaining individual bridges rather than laboratory study with prescribed conditions.

Inspection

The development of NDT tools is highly expected. NDT tools in the market are supposed to work based on theoretical background and laboratory tests but they sometimes do not work well in the field. Accordingly, we are planning to start a project in cooperation of highway administrators. We'll choose several bridges that will be repaired and the scaffolding will be attached to throughout Japan to give opportunities to industry to test many kinds of nondestructive testing tools. The result on the accuracy and feasibility will be shared with highway administrators and developers. We expect that this effort will show developers the clear needs of improvement and highway administrators the potentials of newer technology.

Autopsy and scientific trials using decommissioned bridges

When any damage is noticed for a certain structural member or portion of the bridge, the urgency, priority, and required level of corrective action depends on how much that damage can affect the bridge system structural performance. Because each bridge has the uncertainty of structural conditions, it is difficult to assess the precise degree of structural soundness. Now CAESAR and highway administrators cooperatively conduct several projects in autopsy survey using bridges that will be decommissioned. Figure 11 illustrates a concept of the autopsy research approach for structural safety assessment. For example, as for concrete bridges, we conduct load tests using bridges that will be decommissioned or members that were replaced while we also disassemble them to survey the corrosion of reinforcement, deterioration of concrete, and so on. Using this approach, we will associate the actual load bearing capacity of older or damaged bridges with the degree and condition of damage and develop a methodology to identify relevant numerical parameters for calculation, resulting in the assessment of the remaining load bearing capacity and deterioration rate of older or damaged bridges. This research also may lead to set replacement criteria for older bridges in the future.

The on-going ``wow" project that should be highly intriguing is using a large-span steel truss and girder bridge of Choushi Oh-hashi bridge (Figure 7). Many large-parts of the bridge are sampled to transport to the CAESAR large-scale structural test laboratories. CAESAR researchers will scrutinize many issues to improve the inspection technique for finding structural deficiencies and the prediction technique for estimating the remaining strength of deteriorated critical structural components. For example, the structural members are going to be inspected with many NDE (non destructive evaluation) methods and then disassembled such that we can compare the predicted and real conditions. The strength of those members is also going to be tested and compared with numerical predictions in which the input data are derived from NDTs and/or disassembled results. As of June 30th, 2009, the researchers already have conducted a visual-based bridge inspection, trial of an NDT tool for the estimation of remaining steel thickness, vibration test, truck loading test on site. In addition, they also have looked over the history of earlier rehabilitation works and started furnishing finite element models.

One other on-going project is the autopsy study using Asahi Bridge (Figure 12). The bridge is three-span continuous steel I-girder bridge located in Hokkaido. It was built in 1953 and decommissioned in this last December because of functionally obsolete. A truck load test, vibration test, and non-destructive evaluation for decks were conducted on site from last October to December and a series of fatigue load test of a part of the deck plate, using a wheel running testing machine and numerical simulations for the bridge and deck behavior will be carried out.

Follow-up investigation of repair/rehabilitation case histories

CAESAR conducts a three-year project to design the follow-up database for the effectiveness and durability of earlier repair and rehabilitation work in actual bridges in real environments. Most corrective measures/chemicals/materials come to the market via laboratory tests and theoretical research. However, they often do not have sufficient data in the field to see if those are effective and durable in any conditions. We acknowledged that sometimes they work well and sometimes they do not work well for bridge by bridge. Accordingly, the follow-up database will give highway administrators the direction of relevant choice of repair and rehabilitation methods considering the surrounded environment, age, bridge structural type, position and type of structural members, level of deterioration and damage, traffic volume etc.

So far, as stated above, seeds of industry and needs of highway administrators are somewhat different. The follow-up database also will give strong directions to industry what is needed, what should be improved, and what should be tested before hitting the market.

Long-term bridge monitoring of deterioration

Long-term bridge monitoring is also a key to model the deterioration of bridges and verify design technology for durability. However, long-term and reliable observation results in the field are rare. It is therefore necessary to accumulate findings associating continuous monitoring data, periodical thorough inspection results, and the change in the load-bearing characteristic of the structure with each other. CAESAR and Okinawa Prefecture just have started a 100-year collaborative project to obtain the long-term observation data for chloride-induced deterioration of concrete bridges and corrosion of steel bridges. Okinawa islands are the southern part of Japan and designated in the code as the region at which a special treatment is required for preventing chloride-induced deterioration. Many bridges in the islands suffer from chloride-induced deterioration and corrosion and there are many long span bridges between islands. Accordingly, the effective data acquisition is a keen strategy to conduct preventive maintenance at the right time with the right method. Irapu Oh-hashhi Bridge as shown in Figure 13 will be used for a special investigation. Irapu Oh-hashhi Bridge is a prestressed concrete bridge that is designed under the latest codes of practice in terms of the durability against chloride-induced deterioration. It is now under construction and will be completed in 2010. In some parts, the cover concrete of the piers is designed to have an additional thickness so that samples can be obtained to monitor the time evolution in the chloride penetration into concrete during 100 years after the completion. When the sampling will be conducted, many NDT tools also will be tested for comparison. In addition, many sample specimens are also going to be made when the concrete is cast at piers and will be delivered to exposure tests. Because there should be some allowable difference in the material property of concrete of the piers, we will see the differences in the deterioration condition of the piers for a long time because of the deference in the fresh concrete quality, cement quality, and environmental conditions. On top of that, other 10 bridges with longer spans also will be inspected to model the time evolution of the on-site chloride penetration and strength of concrete. This project is very beneficial for both parties to establish reasonable behavior curves, so that they will be able to make the bridges' lives longer than 100 years. Other highway administrators also have interests in starting similar projects.

We expect that this kind of long-term observation, follow-up investigation of earlier corrective measures, and autopsy survey of heavily damaged bridges will strongly improve the micromanagement technology of individual bridges such as behavior curves, reasonable structural safety evaluation algorithms, and the right choice and timing of method to repair.

6. DATABASE APPROACH

NILIM and CAESAR cooperate to promote database approach. For example, the nation-wide bridge inspection result is kept scrutinizing to seek more reasonable inspection frequency and items. The change in the trend and distribution of nation's highway bridge conditions is also kept tracking down based on the inspection database to invent scientific indicators effectively enough to measure the performance of earlier and future maintenance initiatives.

7. REMARKS

CAESAR is organized especially to be able to respond precisely and timely to needs of society and highway administrators in a flexible manner beyond the framework of typical studies in the laboratory. The scientific trail approach is considered to be crucial while basic research also runs. The acronym CAESAR was inspired by Julius Caesar of the Roman Empire, who established and maintained the infrastructure of long empire-wide highway network -- parts of which are still in use more than 2000 years later. We hope our new CAESAR research center will forge ahead with an equally strong will, and thus ensure we can complete our missions. Collaborative work with related research organizations will be highly appreciated.

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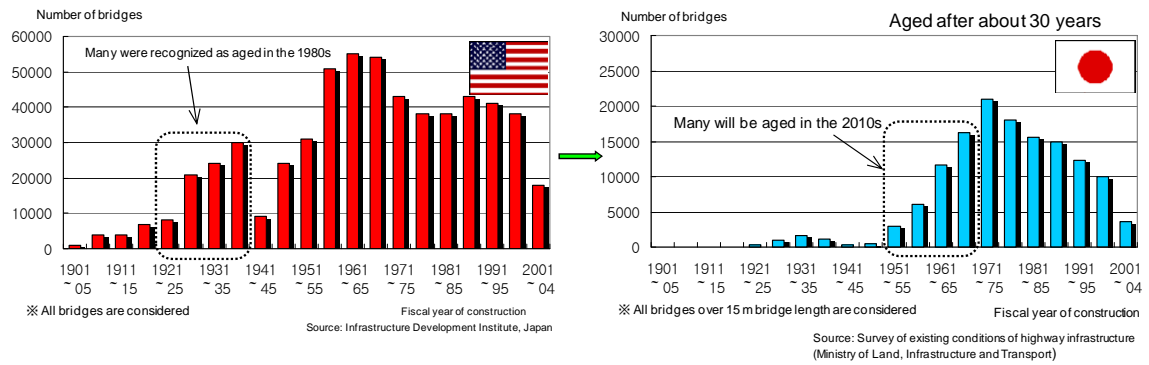


Figure 1. Transition of the number of highway bridges by fiscal year of construction in Japan and the U.S.

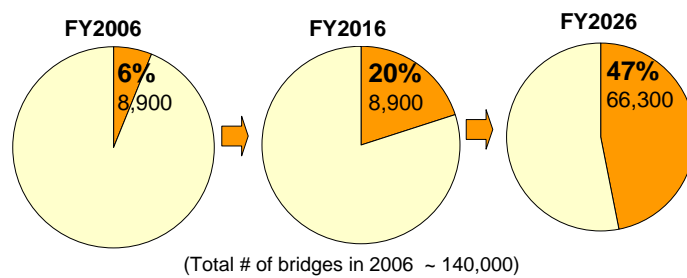


Figure 2 Percentage of bridges of ages 50 and older (No shorter than 15 m)

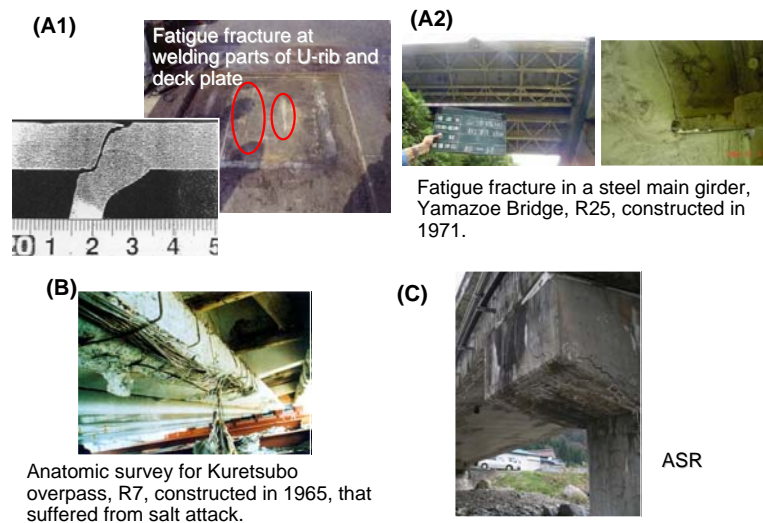


Figure 3. Three major types of distress that severely impact bridge strength capacity: A = fatigue fracture in steel members, B = chloride-induced deterioration of concrete structures, and C = alkali silica reaction of concrete structures.

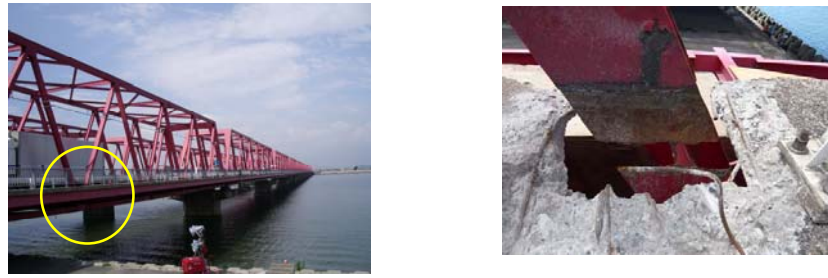


Figure 4. Fracture of a truss bar covered in concrete deck due to severe corrosion (Kiso River Oh-hashii Bridge, R23, constructed in 1963)

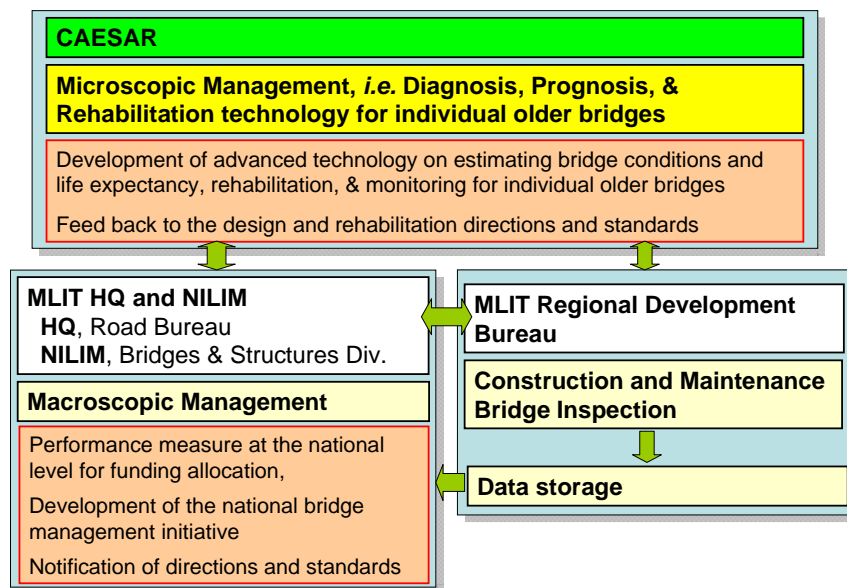


Figure 5. Organizational chart of national highway bridge administration system

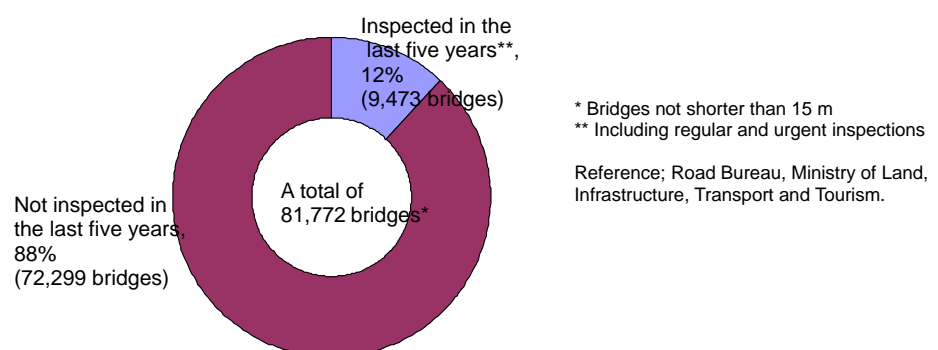


Figure 6. Number of inspected or not inspected bridges in the last five years that are operated by community governments such as cities, towns, and villages in Japan as of 2007.9.

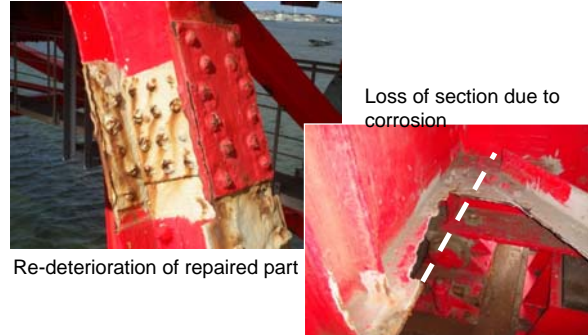


Figure 7. New and old Choshi Oh-hash Bridge

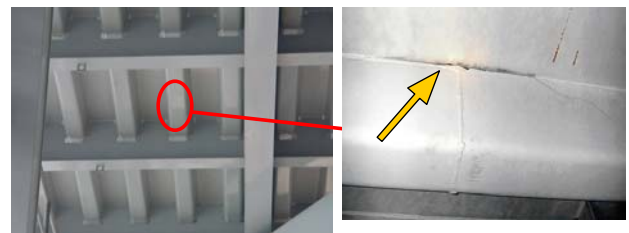


Figure 8. Fatigue fracture of the welding part between U-rib and deck plate

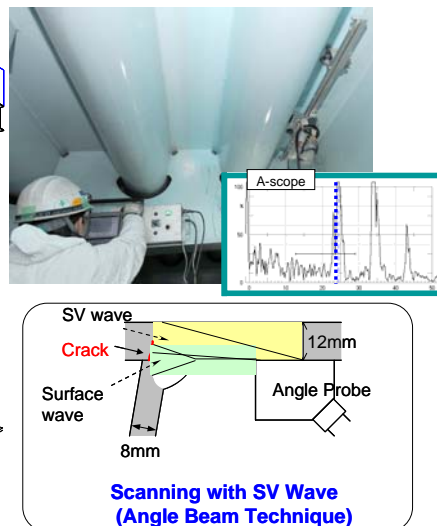
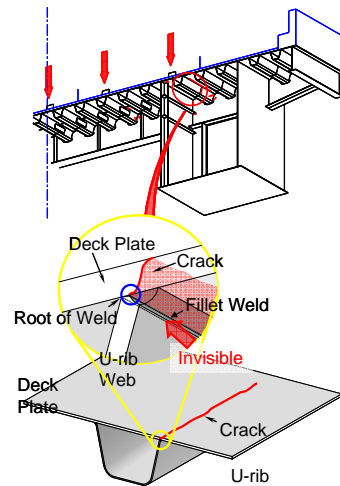


Figure 9. A new UT tool to detect fatigue cracks in steel floor decks

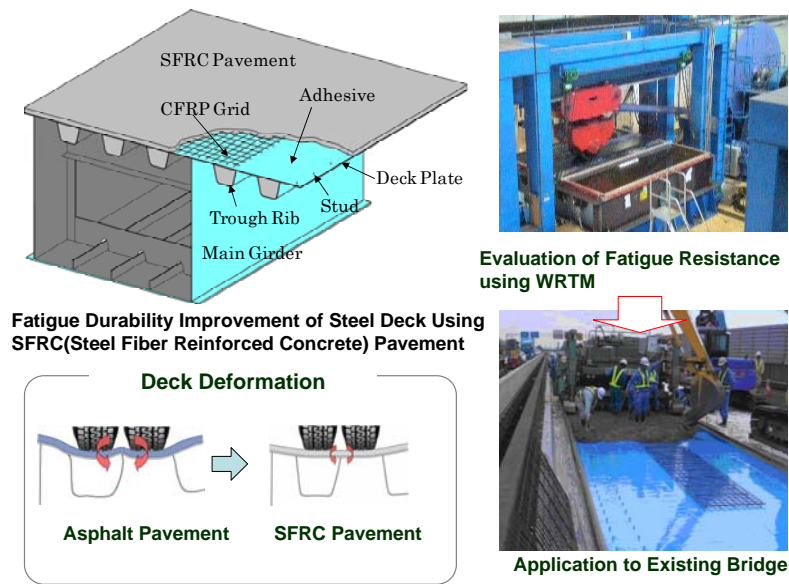


Figure 10. Fatigue durability improvement technology of existing steel floor deck using steel fiber reinforced concrete (SFRC) pavement

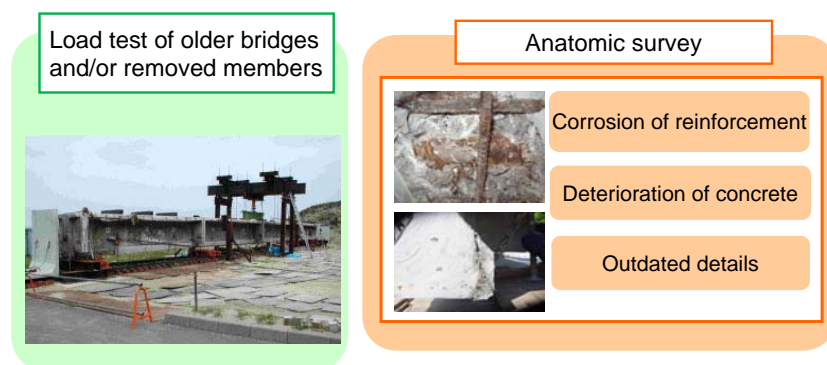


Figure 11. A concept of the autopsy survey to develop the load-carrying assessment technologies for damaged bridges



Figure 12. Asahi Bridge: 3-span continuous steel girder bridge constructed in 1953

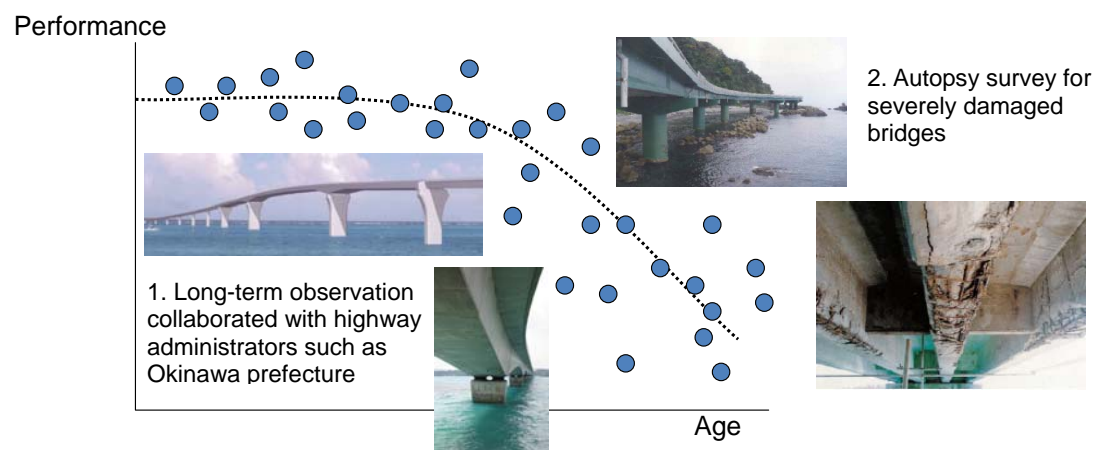


Figure 13. A concept of the long-term observational research